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Base Facilities Environmental Quality

Optimum Selection of Clustered Conservation Areas Within Military Installations

Sahan T. M. Dissanayake, Hayri Önal, James D. Westervelt, and Harold E. Balbach

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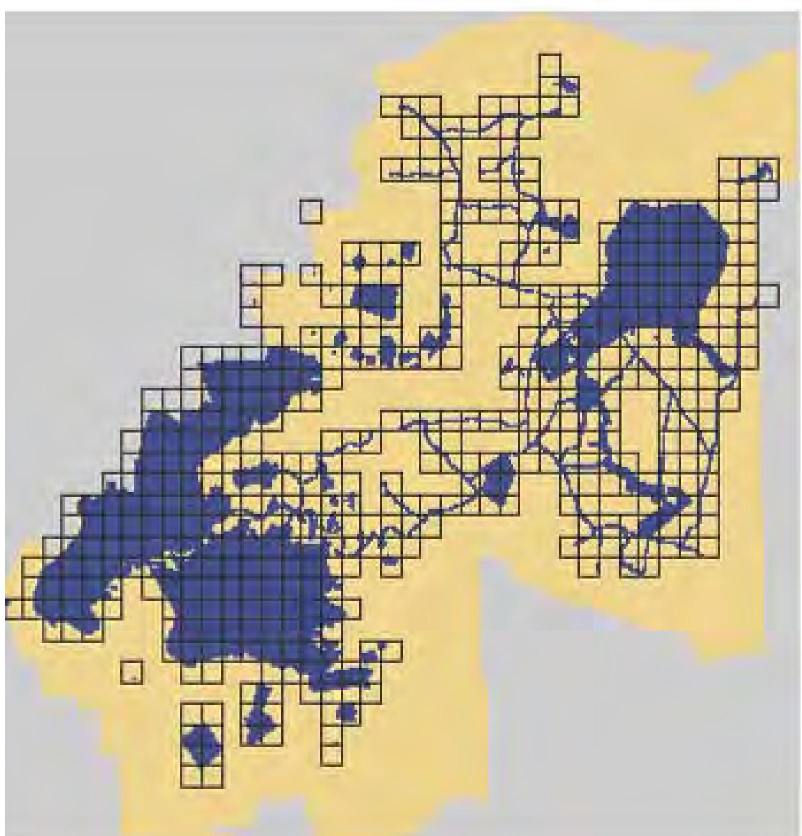

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Optimum Selection of Clustered Conservation Areas within Military Installations

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Abstract: Suitable habitat areas for many rare, threatened, or endangered species in the United States are found inside the boundaries of military installations. Because these same lands are also needed for conventional and emerging training requirements, there is growing need to manage military landscapes in a balanced way that can satisfy competing goals. This study introduces linear integer programming formulations that can be used as a decision-support tool for relocating multiple populations of a species at risk to clustered conservation areas inside a military installation.

The authors present a basic clustered relocation model and extend it to minimize the distances of relocation and to produce "meta-clustering" of separate conservation areas. Two meta-clustering methods are introduced, the first using a constraint and the second using a multi-objective function. The models are applied to a dataset related to the Gopher Tortoise (GT), a keystone species determined to be at risk at Fort Benning, GA. Analysis of the results is presented. The results illustrate that, using integer programming, it is possible to optimally design habitat areas that incorporate spatial and ecological consideration for species relocation where competing land uses must be supported.

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Preface

This study was conducted for the Office of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology (ASA(ALT)) under Research, Development, Test, and Evaluation Program A896, “Base Facilities Environmental Quality (Military Training in the Presence of Species at Risk)”; Project P2 140644, “Multi-Species PVA.” The technical monitor was Dr. Victor E. Diersing, DAIM-ED-N.

The work was performed by the Ecological Processes Branch (CN-N) of the Installations Division (CF), US Army Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL). At the time of publication, William D. Meyer was Chief, CEERD-CN-N; Dr. John T. Bandy was Chief, CEERD-CN; and Dr. Alan B. Anderson was the Technical Director for Military Ranges and Lands. The Deputy Director of ERDC-CERL was Dr. Kirankumar Topudurti and the Director was Dr. Ilker Adiguzel.

COL Kevin J. Wilson was the Commander and Executive Director of ERDC, and Dr. Jeffery P. Holland was the Director.

1 Introduction

1.1 Background

Suitable habitat areas for many rare, threatened, or endangered species are located in the vicinity of military installations in the United States. While some habitat deterioration is caused by military training, it is often observed that the military ownership of these lands protects them from more destructive and permanent urban and agricultural development. In addition to isolating these lands from extractive economic uses, the Department of Defense (DoD) allocates a significant amount of human capital and land for protecting and managing wildlife habitat in and around installations. In 2006, the DoD spent $4.1 billion on environment-related expenses, of which $1.4 billion was for environment restoration and $204.1 million was for conservation [1]. On the other hand, both conventional and new training requirements make it necessary to manage federal lands in the best possible way to balance these competing objectives and land uses. As an alternative to costly solutions, such as purchasing land or acquisition of property rights, more effective utilization of the existing lands for conservation and military purposes can be accomplished by optimizing the landscape to best addresses conservation and military training area needs.

Fort Benning, GA, is one example of a military installation that is challenged with balancing these conflicting objectives. Fort Benning currently has an extensive population of Gopher Tortoise (*Gopherus polyphemus*), referred to as GT, and Red Cockaded Woodpecker (*Picoides borealis*), referred to as RCW. The RCW is listed by the Federal government as endangered, and the GT is listed as a species at risk. As part of an expansion of Fort Benning's mission, new firing range and maneuver areas are being constructed for emerging needs. In an effort to best manage the GT and the RCW populations, Fort Benning is investigating the optimal selection of habitat areas that can be made available for the protection of these two species. Some of the proposed new training areas are heavily populated by GTs, so land managers are considering relocating GTs to lesser-used areas to be selected within the boundaries of the installation.

The University of Illinois and the US Army Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-

CERL) collaborated on the development of optimal land-use strategies by incorporating various ecologically important considerations along with military training requirements. This report presents several models that can be used to incorporate relocation distances and meta-clustering (clustering of clusters of individuals) as spatial criteria in designing conservation management areas (CMAs). We apply the models to a real dataset pertaining to Fort Benning where protection of Gopher Tortoise, a *keystone species* at risk, is of concern. A keystone species is one whose local extirpation will directly result in the extirpation of other species. Many species rely on gopher tortoise burrows for their survival.

Because GT is a ground-bound species, the selected areas should be as compact as possible, preferably contiguous, in order to allow movement of GT in the selected areas and facilitate interaction among individuals in those areas. A compact CMA is also easier to fence, if necessary. Furthermore, it is desirable to minimize the relocation movement distances and also to have the CMAs to form a clustered network in close proximity to each other in order to promote interaction between multiple populations.

In consideration of the above, specifying the most suitable CMAs involves various important spatial considerations, including:

- a minimum size, either specified in terms of the land area or in terms of the GT population in that CMA
- a compact shape, either circular or roughly square
- relatively small relocation distances in order to decrease transportation costs and facilitate each individual's adaptation to its new habitat
- optimal location of two or more CMAs, being close enough to allow interaction between multiple populations but remote enough to reduce the probability that all will be catastrophically affected by disease or unplanned military activities.

1.2 Objectives

The objectives of this work were to

- identify the optimal GT habitat areas in Fort Benning
- determine whether optimum site-selection methods can effectively select habitat areas for species relocation given various ecological criteria, spatial constraints, and conflicting land uses such as military training.

1.3 Approach

The optimum site-selection models described in this report are formulated as linear integer mathematical programs. The programs are implemented using General Algebraic Modeling Software (GAMS), version 2.0.26.8, a commercially available mathematical modeling software package [2]. Four linear, mixed-integer programming models were developed to address the issues noted above. The models are similar, but each includes distinct features that are needed to reflect the spatial requirements considered in site selection. The details of the models are presented in Chapter 2 and the GAMS code for the models is presented in the Appendix.

The models are applied to data from Fort Benning, and the empirical results are analyzed and discussed. The data for the empirical application were obtained as Esri shapefiles from Fort Benning land managers and converted using Esri ArcGIS [3], version 9.3, to a form usable in GAMS. Details are presented in Chapter 3.

1.4 Scope

This study addresses optimal relocation of the affected GT populations from the areas that will be most heavily affected by the new Fort Benning military training demands.

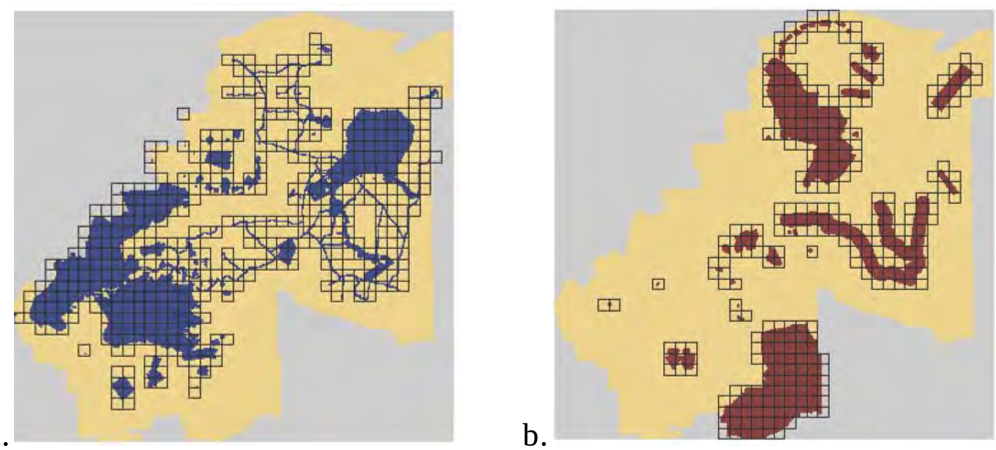
Although the models are mathematically complex, the empirical applications demonstrate that they can be solved within a reasonable computation time for the data set used here.

1.5 Mode of technology transfer

The models described in this report are being presented at conferences and seminars to inform military installation land managers, land managers of conservation agencies, academics and researchers of (1) the ability to incorporate spatial considerations in optimum land selection models to select the best lands for conservation goals and (2) the availability of these models for direct application at various locations. The theoretical contributions of the models are being prepared as a manuscript for submittal to a peer-reviewed journal.

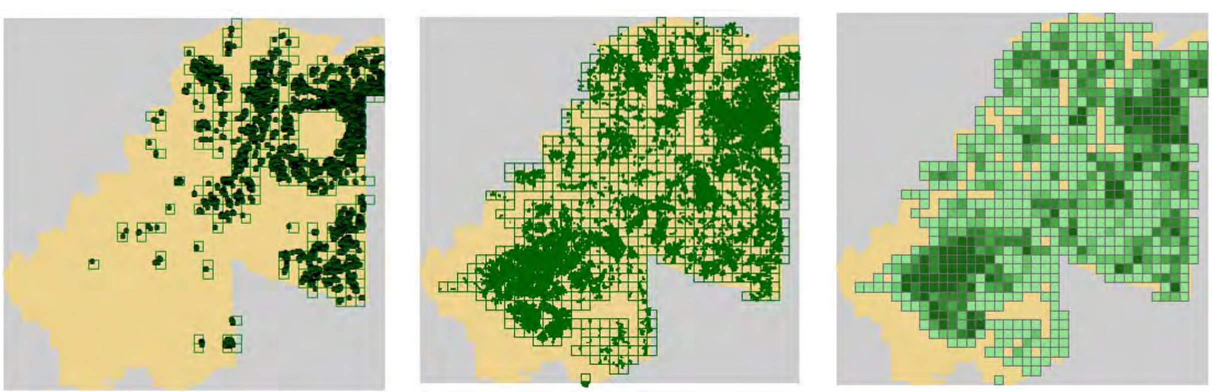
2 Model Development

Figure 1 shows areas of Fort Benning where military use is currently intensive and projected to be intensive to support expanded missions. Figure 3 summarizes the status of current and prospective GT habitats on the installation.



a. b.

Figure 1. Current and projected Fort Benning military land use: (a) locations with current intensive military use; (b) proposed areas for additional intensive military.



a. b. c.

Figure 2. Fort Benning GT habitats: (a) locations based on burrow counts; (b) suitable GT habitat areas; (c) quality of suitable habitat areas (darker shade indicates higher quality).

The current evaluation is essentially identical to that involved in the design of reserves for protection of certain sensitive species, to which the application of mathematical models dates back to the late 1980s [4]. The use of the term “reserve,” however, is not applicable to military installations where protection of certain species and considerations for their management are always subject to mission requirements and Congressional authority. Therefore, we use the term conservation management area (CMA) with regard to the application. In its simplest form, the problem is stated as selecting a minimum number of habitat sites that contain populations of a specified set of species, or maximizing the number of species that can be managed under a conservation budget constraint or area limitations. Both problems are formulated as linear integer programs (IP). Typically, both types of optimum site-selection models result in highly sparse and dispersed CMA configurations. Recognizing this deficiency, several integer programming models have been developed in recent years to incorporate various forms of spatial considerations, such as CMA connectivity, compactness, fragmentation, buffer zones, etc. (see [5] for a review). This type of consideration generally requires a much more complex mathematical formulation and large-scale models. As discussed earlier, in the problem addressed here, spatial coherence of the designated GT CMAs is particularly important. Alternative formulations are presented below, each incorporating a different spatial criterion to determine an optimal assignment of areas to conservation based on the site characteristics (habitat suitability) and geographical locations.

The models presented below have a common feature in that they consider a grid partition that comprises of square land parcels[1], each of which will be referred to as a *site*. Each site is assumed to be an independent decision unit. When selecting sites to configure a CMA, the locations of individual sites relative to other selected sites and their contributions to the conservation of GT are taken into account simultaneously. More specifically, a CMA is characterized by a central site and a set of sites packed (i.e., clustered) around that central site, as shown in Figure 3, where C_1 indicates the central site and S indicates sites selected as part of the CMA. Figure 3a represents a scattered CMA and Figure 3b represents a clustered CMA. The problem is to determine the central site of each CMA and to assign individual sites to the CMA in an endogenous way while satisfying the conservation requirements and considering alternative spatial criteria in cluster formation[2]. For each specification of the spatial criteria considered in site selection, a linear integer program was formulated. The algebraic details of the models are not presented in this report, but can be found in

[1] The square-cell assumption is not a requirement. The approach developed here can be applied to other geometric forms, such as triangles, rectangles, polygons, or even irregular forms.

[2] This model is an extension of classic p-median problem [28]. Similar models for clustering have been used previously in the literature of reserve design, business districting, and political districting [21, 27].

Dissanayake, Önal, and Westervelt [6]. Each model, however, is associated with an *objective function*, which is an algebraic statement that results in a value that will be minimized or maximized. For example, in the base model described below, the objective is to minimize the sum of the distances between all selected parcels and their associated cluster center. Each model is associated with constraints that can be expressed algebraically (e.g., the total number of clusters must equal 3) or in the form of information about parcels provided in the form of GIS raster maps.

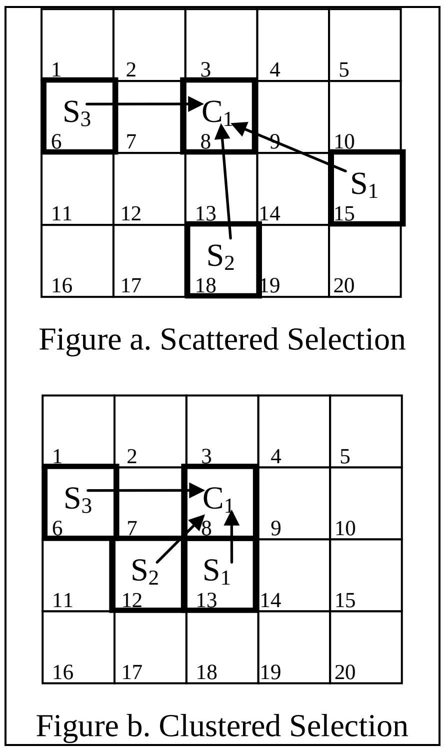


Figure 3. Model representation of a CMA.

2.1 Base model

We first address the problem of constructing *n* compact CMAs, each covering a minimum sustainable GT population and collectively covering a desired GT population. The compactness of a CMA is defined as the overall "closeness" of all sites in it. We measure this by the sum of distances from all sites to a central site in each cluster, which must be minimized to the greatest extent possible[3]. The model that serves this purpose is referred to here as the *base model*.

The model solution is the most compact collection of sites that meets the population requirements. The model achieves a clustered solution by minimizing the distances from individual sites in each CMA to the center cell of that CMA, which in turn is summed over all CMAs. The model ensures that *n* CMAs, each of which supports a population that exceeds the minimum sustainable size[4], are created. Further, the model ensures that all CMAs collectively support a desired total population.

The base model does not incorporate the relocation distances and does not consider the location of individual CMAs relative to other CMAs in the network. However, the base model is extended below to include these considerations.

2.2 Optimal relocation model

As can be seen by comparing Figure 1 with Figure 2, the installation's proposed new military training areas contain many GT populations. Therefore, GT populations in those locations must be moved to new habitat areas that will be selected from among areas in Figure 2 that are not planned for additional training uses. The relocation model seeks to select the best CMAs and determine optimal relocation of the existing GT populations that are within the planned new military training areas. The selection of those parcels must be done in such a way that

- provides compact CMAs
- makes CMAs large enough to support a sustainable GT population that accommodates all GT populations currently located within the planned expansion areas
- moves the existing populations the minimal feasible distance.

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[3] Compactness is not a well defined concept. Note that the absolute value of the compactness measure defined here may not mean much by itself, but must be considered together with the size of the reserve (number of sites involved). This is because a reserve with only a few distant sites may have a smaller total distance value than a reserve with too many tightly packed sites, whereas in practice the latter should be considered more compact. Although not being fully satisfactory, this definition well serves the specific purposes of the present study. Minimizing the total distance typically results in a circular and connected CMA configuration.

[4] This constraint can also be expressed in terms of a minimum number of parcels or CMA if the effectiveness of conservation effort is related to the reserve size.

The first two criteria are satisfied in the base model formulation. The third criterion is intended to maximize the survival probability of the GT populations that are relocated based on an assumption that if the relocation distances are small, the GT populations are more likely to adapt to their new environment considering that it closely resembles their original environment[5]. It should be noted that the model can be easily adjusted to maximize the movement distances if it is desirable to have the individuals located a considerable distance from their original habitat areas.

It is assumed that the entire population in a given site is moved together to a new area; no relocation of any separate portion of the population is allowed. We first introduce a basic *relocation model*, which solves the relocation problem, and then expand the model to include relocation distances and meta-clustering considerations. The model described below, called Relocation Model I, solves the optimal site-selection and relocation decisions: A detailed description of the model can be found in Dissanayake, Önal, and Westervelt [6].

Relocation Model I is mostly identical to the base model, but includes the following two additions:

1. The model ensures that for each CMA, the sum of the existing GT population and the new GT populations moved to that area does not exceed the carrying capacity of that CMA, which is the sum of the carrying capacities of individual sites included in that CMA.
2. The entire population in each new military training site is moved to one and only one CMA.

The second constraint was added because GTs are believed to have social interactions, so keeping neighboring populations together is expected to reduce the negative impact of relocation. Next, we extend Relocation Model I to minimize the movement distances and to incorporate meta-clustering formulations.

[5] The relocation distances in the model can be replaced with costs attributed to the move. Although relocation (travel) costs were not considered in this application, it can be a significant consideration in many other applications. The model can be easily modified to directly minimize relocation costs by replacing d_{lk} in the objective function with c_{lk}, where c_{lk} is the travel cost between site l and site k.

2.3 Minimum distance relocation model

For the minimum-distance relocation model, called Relocation Model II, we extend the objective function to include the movement distances. Therefore the objective function consists of two parts:

- the sum of distances from sites in the selected CMAs to the centers of those CMAs, as in the Relocation Model I, which achieves the clustered solution
- the total distance that all GT populations are moved.

The model simultaneously maximizes the clustering (by minimizing the sum of the distances) and minimizes the movement distances. The model explicitly considers the tradeoff between CMA compactness and the relocation distances in a unified framework and determines a compromise solution.

Although this model considers the locations of selected sites relative to the central sites to which they are assigned, it does not consider the location of the CMAs relative to each other or their locations with respect to the surrounding land. Therefore, the model is indifferent between two CMA configurations where one CMA network includes closely placed multiple CMAs while the other includes remote CMAs as long as the specified conservation targets are satisfied and the movement distances are minimized. Incorporating such aspects may have significant impact on site-selection decisions. These issues are addressed in the modified meta-clustering formulations below.

2.4 Meta-clustering models

The *meta-clustering model* extends Relocation Model I to incorporate distances between multiple CMAs so that not only are the sites in each CMA compact, but also the CMAs themselves are close to each other. We present two meta-clustering formulations. Meta-Clustering Model I places an absolute distance criterion on meta-clustering by limiting the maximum distances between the CMAs and a *meta-center* (i.e., the site identified as the center of the CMAs). Meta-Clustering Model II is a multi-objective model that incorporates distances from individual CMA centers to a meta center in the objective function.

In the first approach, Meta-Clustering Model II, the only change from Relocation Model I is an additional constraint that restricts the distance between each pair of CMAs to a specified maximum distance, denoted by $\bar{d}$. Thus, this approach groups CMAs together and leads to a compact constellation of CMAs if $\bar{d}$ is made sufficiently small.

In the second approach, Meta-Clustering Model II, the objective function in Relocation Model I is modified by adding a term that incorporates the distances between the centers of the selected CMAs. The objective function now contains a first term, which is the sum of the distances from the sites in a CMA to the center of that CMA; and a second term, which is the sum of distances between selected CMA centers and the meta-center (i.e., the center of all the CMS centers). Therefore the model explicitly considers the tradeoff between CMA compactness and meta-clustering of the CMAs and determines a compromise solution. The second term in the objective function requires a new variable to identify the assignments between CMA centers and the meta-center. Therefore, three additional constraints are introduced to govern the selection of the meta-cluster. The new constraints ensure that there is only one site selected as the meta-cluster center and that every CMA center is assigned to the meta-cluster.

2.5 Data

Data processing and model implementation were accomplished using commercially available software. The data on current and future military training areas were obtained as raster files from Fort Benning (see Figure 1). The habitat areas suitable for GT were obtained as raster files from the national biological information infrastructure [7], then converted to Esri shapefiles using ARC GIS 9.2 (see Figure 2). A 40 x 40 grid file, in which each grid represents 900 x 900 m, was created using GeoDa, and the grid shapefile was spatially joined with the above shapefiles using the Spatial Join tool in ARC GIS. This tool gives the grid file the attributes of the shapefile. To ensure that each grid cell represents a density of the original data, the "sum" option was used when joining the GT burrow data and the habitat suitability data.

The grid cell values for Figure 1 are specified as binary values (grid cell value = 1 if cell includes a base area or a planned expansion area). The grid cell values for Figure 2 are given as an index. For Figure 2a, each grid cell value is the sum of the number of observed GT burrows within the grid cell, the index ranging from 0 – 350. For Figure 2b, the grid cell value is the sum of the GT-suitable points (the GT suitability raster map was converted to a point shapefile) within the grid cell. The suitability index ranges from 0 – 864. A GT population density parameter is used with this grid cell value to reflect the sustainable number of GTs for each CMA. A 1 hectare land parcel can support between 2 to 4 GTs. This is equivalent to supporting between 180 – 360 GT per site at the 900 x 900 m resolution. Therefore, the GT population density parameter is set to 0.5 for the empirical analysis described in Chapter 3.

3 Results and Discussion

This chapter presents the results produced by Relocation Model I, Relocation Model II, and the two meta-clustering models. All models were solved using GAMS/CPLEX version 21.6 on a personal computer running Microsoft Windows XP with an Intel Core 2 Duo processor and 2 Gb of RAM.

The total population of GT that may need to be relocated is estimated to be at least 1,800. This number is based on actual burrow counts in the areas that will be allocated exclusively to military uses (as shown in Figure 1).

Because there are existing GT populations in the potential CMAs, we needed to consider an overestimate of this figure when restricting the minimum population size that the entire conservation area should hold after relocation. Here we assumed that the final total population in all CMAs (including the existing GT populations and the relocated populations) is at least 4,000. In theory, the GT populations that are currently located in the planned military expansion areas can be moved to a single large CMA or multiple smaller CMAs, which are all located outside the area that will be required for intensive military use. We require the CMAs to be as compact as possible and assume that sites belonging to the intensive-use maneuver zones are not eligible for selection. The model is solved with various parameter specifications for the number of CMAs. There are three reasons for specifying more than one CMA. First, we may want to separate the relocated GT population into smaller populations, each being located in a different part of the CMA, to safeguard them against potential disease outbreaks that may occur in a managed area and spread to the other areas. Second, one large CMA requires movement over large distances of several populations located in different parts of the new training zones. This might create a more challenging adjustment problem, particularly for the populations relocated to distant areas. Third, setting aside one large conservation area reduces the flexibility for the installation if further expansion of training areas is needed in future. These problems can be mitigated by designing multiple small conservation areas.

In all of the model runs discussed below, the minimum population for each CMA was specified as 750 and the minimum total population was specified as 4,000. Relocation Model I and Relocation Model II were solved for one, two, three,

and four CMAs. The two meta-clustering models were each solved for four CMAs. These numbers are specified arbitrarily to illustrate the workings of the models and demonstrate the tradeoffs between different spatial criteria.

3.1 Base relocation results

Relocation Model I results, without spatial considerations other than compactness of the selected CMAs, are shown in Figure 4 for one, two, three and four CMAs. Comparing the result with the suitability map given in Figure 2c illustrates that the base model simply selects from among the most densely packed and best available sites to form contiguous and compact CMAs. The optimal solution with one large CMA (Figure 4a) shows that this area would be located at the southeast corner of the installation. However, the compactness of the CMA is poor; the 16 selected sites are meandering in shape. This result is driven primarily by the facts that the model is forced to choose one cluster of habitat sites and the only available good-quality sites not currently populated heavily by GT are in that part of the installation. The good-quality sites in other parts of the installation are not in the solution because those sites are under extensive military use, or the high density of GTs currently inhabiting those sites prohibits relocating new GTs there, or the suitable sites are located too far apart from each other to form a compact CMA.

For the two-CMA case, the model chooses two clusters with four and eight sites, respectively (Figure 4b). The three-CMA case selects a total of ten sites (Figure 4c), and the four-CMA case selects 11 sites (Figure 4d). Unlike the one-CMA scenario, the two-, three-, and four-CMA configurations produce compact clusters of sites since inter-site distances are accounted for each cluster separately rather than in aggregate, which allows the model to select closely located sites from multiple locations. Based on these results, we may conclude that if the size of the total area dedicated to CMAs is a concern, forming three CMAs—two located in the southwest and one located in the north-central areas—would be the best strategy because it involves the minimum number of sites (i.e., 10).

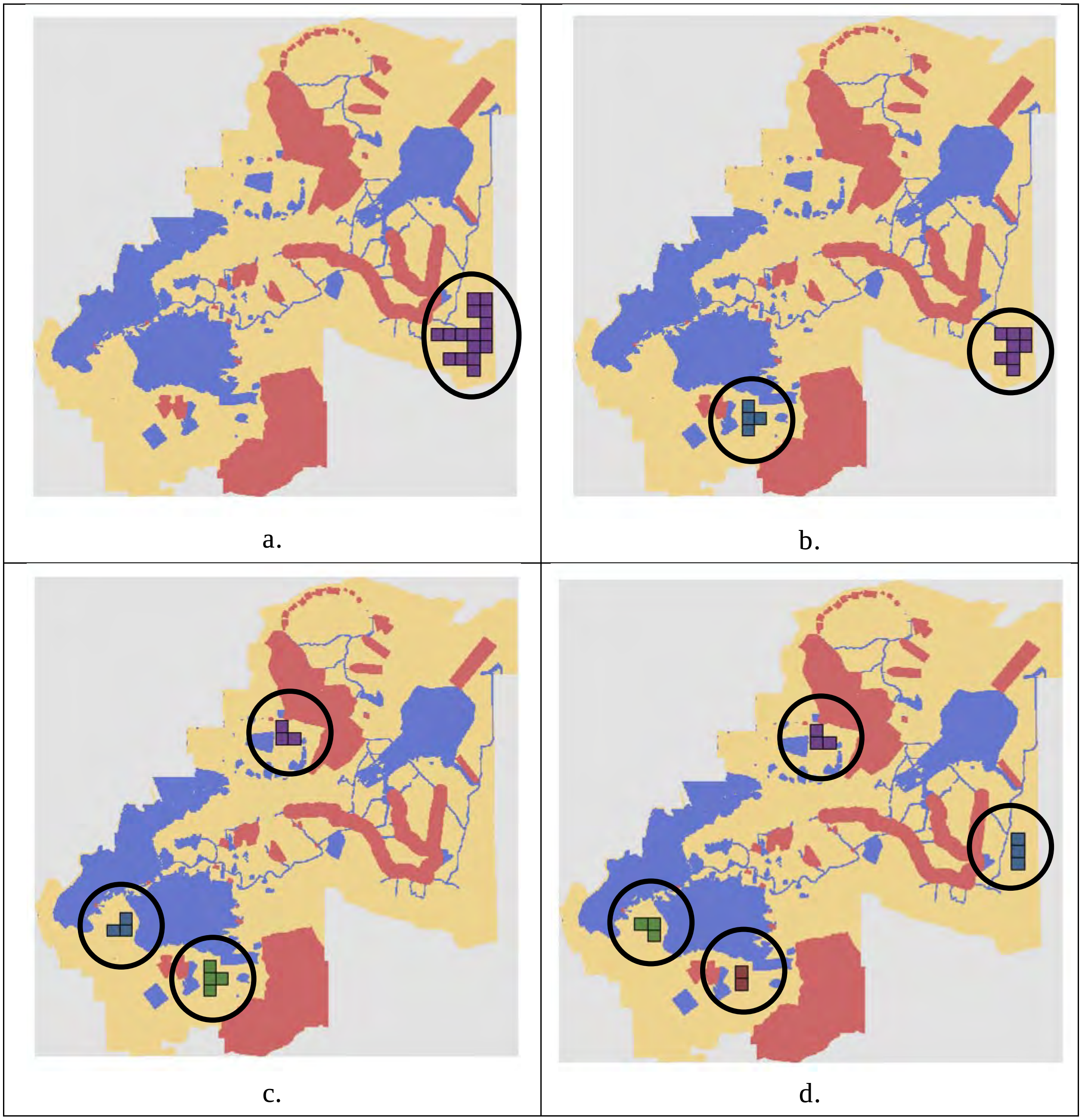

Figure 4. Relocation Model I compact configurations with (a) one CMA, (b) two CMAs, (c) three CMAs, and (d) four CMAs. The lighter shaded areas indicate the current (blue) and proposed (red) military training areas; darker shaded areas (shown with the parcels included) indicate the conservation sites chosen by the model. Black circles indicate the selected CMAs.

3.2 Minimum relocation distance results

The results of the minimum relocation distance model are shown in Figure 5. The optimal solution with one large conservation area (Figure 5a) is again located at the southeast corner of the installation, but slightly different from the solution displayed in Figure 4a and with poorer compactness.

Among the 16 selected sites, one site is disconnected from all the others. Besides the reasons discussed above, minimizing the relocation distances as an additional consideration works against the primary objective of compactness when only one cluster is being selected.

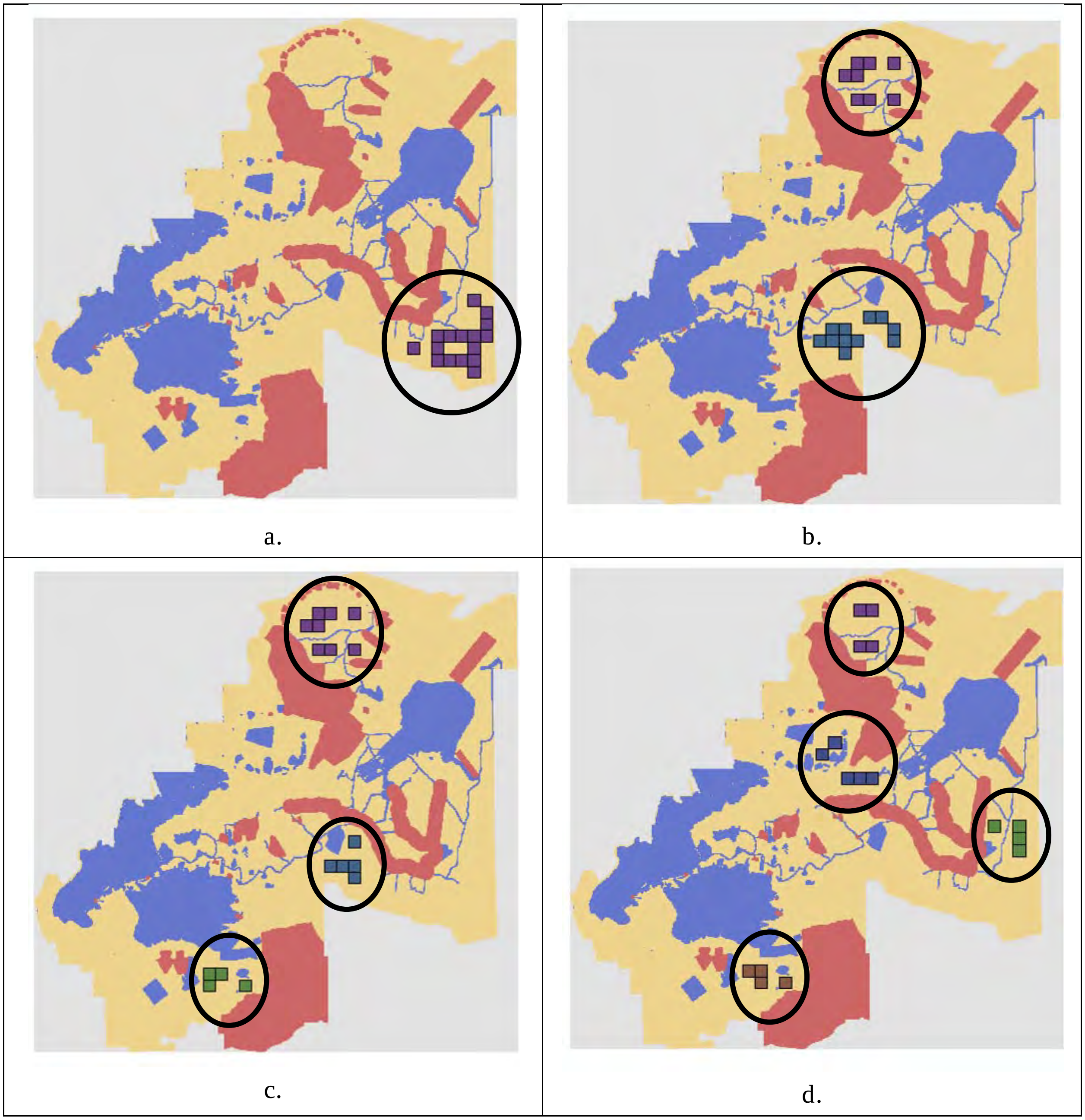

Figure 5. Relocation Model II compact CMA configurations that minimize movement distances with (a) one CMA (b) two CMAs (c) three CMAs, and (d) four CMAs. Lighter-shaded areas indicate the current (blue) and proposed (red) military training areas, while the darker-shaded areas (shown with the parcels included) indicate the conservation sites chosen by the model. Black circles are used to identify the selected reserves.

The results for two CMAs are shown in Figure 5b. The change in the CMA locations is dramatic when compared with Figure 4b. Incorporating relocation distances in the objective function, in addition to compactness, moves the selected clusters toward the top center and bottom center of the installation. None of the southeastern sites was chosen. Instead, eight sites in the north and 11 sites in the south are selected to form the two CMAs. Compared with Figure 5a, this selection minimizes the movement distances from current GT habitats. Also, it has smaller population size requirements for individual CMAs, allowing selection of smaller CMAs with better habitat quality, which was not possible in the one-CMA scenario.

The results for three and four conservation clusters are shown in Figure 5c and Figure 5d. Once again a dramatic change occurs in the CMA configuration compared with the results in Figure 4c and Figure 4d. For the three-CMA scenario, the model chooses 17 sites that are centrally located and relatively close to the area from which GTs are to be relocated. The model does not choose any site from the highly suitable southeast corner because the movement distances to those sites are greater. For the four-CMA scenario, the model chooses a total of 16 sites, again among the centrally located areas. Four sites in the southeast (the best ones identified for the one-CMA solution) form a CMA in that area that is much smaller than the first solution, and three small CMAs are formed in the northeast, central and southern parts of the installation (Figure 4d). This result is driven by habitat quality and relaxed CMA size limitation as well as the preferred compactness property and the goal of reducing total relocation distance.

A clear distinction between the CMAs seen in Figure 5 and the ones in Figure 4 is that the four CMAs found without consideration of relocation distances are much more compact. This is an intuitive and expected result, indicating the tradeoffs between the competing objectives of shorter relocation distances and compactness of individual CMAs. Another evident distinction between the two sets of CMA configurations in Figure 4 and Figure 5 is that the relocation model selects larger clusters of sites as compared with the model that considers compactness only. This result is driven jointly by the relocation distances and habitat qualities of individual sites. More specifically, consideration of relocation distances favors the sites that are closer to the current GT habitats, which are (in this dataset) of poorer quality than the remote but higher-quality sites shown in Figure 4. It should be noted that the weights assigned to the CMA compactness and total distance of relocation objectives heavily influence the outcomes.

Assigning a higher weight to compactness results in more compact, and usually contiguous, CMA configurations. Conversely, placing a higher weight on relocation distance shifts the CMA locations toward the proposed military training areas, which typically reduces the compactness of individual CMAs.

3.3 Meta-clustering results

The results of Meta-Clustering Model I are shown in Figure 6. To highlight the role of meta-clustering, only the results for four CMAs and four different inter-CMA maximum distance specifications ($\bar{d}$) are presented. We measure the distance between any two CMAs by the Euclidean distance between the central sites of those CMAs. The four distance specifications considered were $\bar{d}$ equals (a) 30 cells (27 km), (b) 25 cells (22.5 km), (c) 20 cells (18 km), and (d) 15 cells (13.5 km).

The results for a maximum inter-cluster distance of 30 cells are presented in Figure 6a. The results are identical to the base-case results for four CMAs, implying that the maximum distance constraint is not actually binding. Decreasing the maximum distance specification alters the meta–clustering solutions as shown in Figure 6b – 7d. For instance, reducing the maximum inter-cluster distance from 30 to 25 cells (Figure 4b) moves the southwest cluster to the southeast, a region that has a large aggregation of suitable sites. In both cases a total of 11 sites are selected for the four-CMA case, but the selected CMAs are much closer to each other (compare Figure 6b with Figure 6a). Figure 6c displays the results for a maximum inter-cluster distance of 20 cells. Two of the southwest CMAs are now moved the northeast area because of the availability of equally suitable sites in that area within close proximity to each other. Figure 6d displays the results for a maximum inter-cluster distance of 15 cells. This forced the selected CMAs to be tightly packed, where all four clusters are located in the southeast area and are adjacent to each other, forming a large CMA similar to the base-case solution with a single cluster.

As the maximum inter-cluster distance is reduced, the set of suitable and available sites decreases, forcing the model to choose a larger number of less-suitable sites. In Figure 6a and 7b a total of 11 sites are selected in each case, whereas in Figure 6c, 13 sites are selected, which increases to 14 sites in Figure 6d.

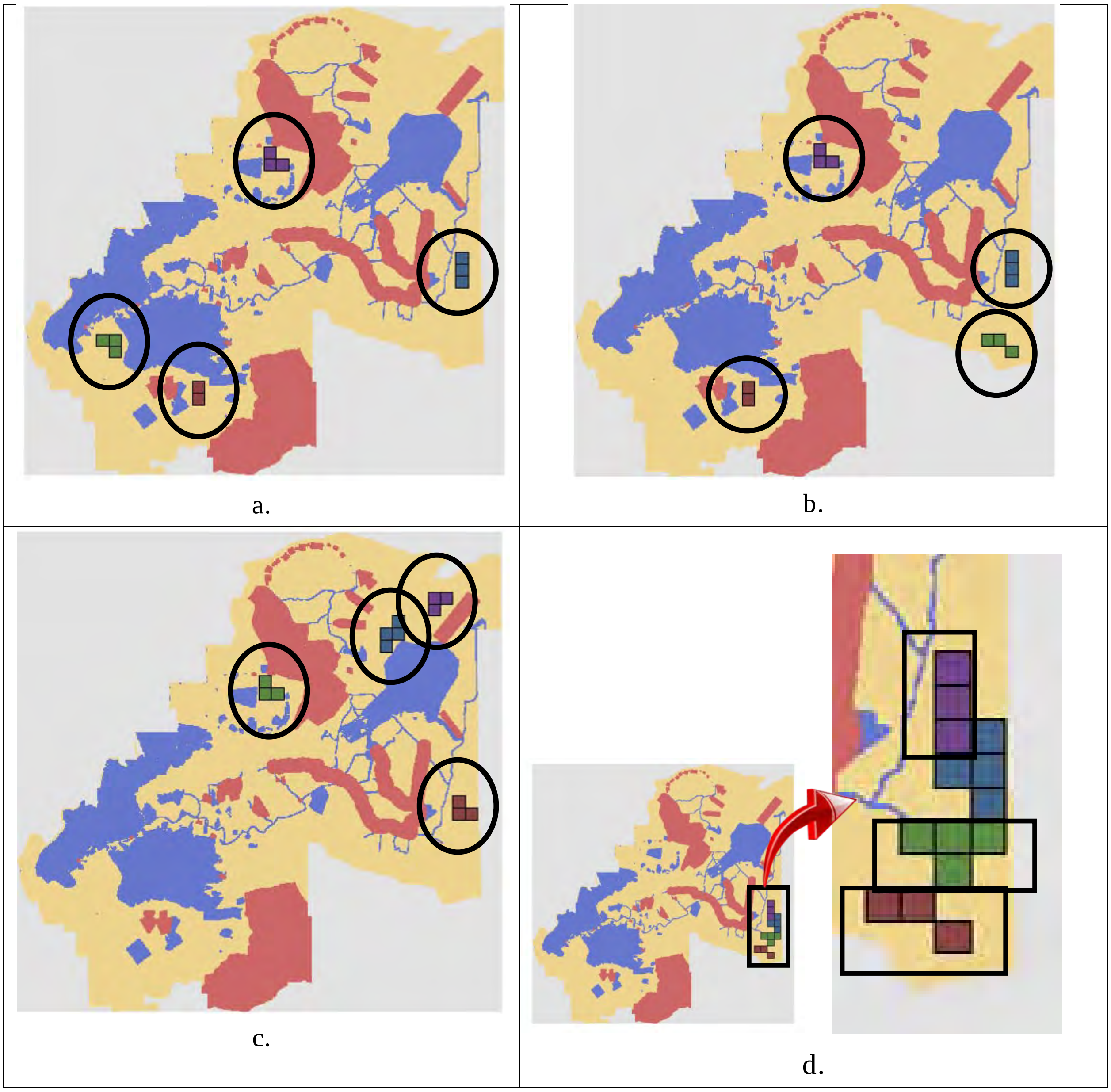

Figure 6. Meta-Clustering Model I solutions for compact CMA configurations constrained by meta-clustering for four CMAs with a maximum inter-site distance of (a) 30 cells (27 km); (b) 25 cells (22.5 km); (c) 20 cells (18 km); (d) 15 cells (13.5 km). The lighter shaded areas indicate the current (blue) and proposed (red) military training areas; darker shaded areas (shown with the parcels included) indicate the conservation sites chosen by the model. Black circles identify the selected CMAs.

Figure 7 shows the results of Meta-Clustering Model II in which clustering is achieved by penalizing the dispersion of CMAs in the objective function. A weight (σ) is given to the meta-clustering component in the objective function to change the penalizing amount. Again, to highlight the model's performance we present only the results for four CMAs and four meta-clustering weights (σ), specifically $\sigma = 0.00$, 0.06, 0.09, and 0.10.

The results for $\sigma = 0$ are presented in Figure 7a. With $\sigma = 0$, the model objective function becomes identical to the four-CMA base case, and the results are indeed identical to the base case results for four CMAs. The results for $\sigma = 0.06$ are presented in Figure 7b. The selected clusters are located closer together and the maximum inter-cluster distance is reduced compared with the configuration in Figure 7a.

Increasing the weight to 0.09 (Figure 7c) puts three of the four CMAs together in the southeast, with only one CMA being located farther away. This last CMA is needed because forming a sufficiently small and compact CMA from the unselected sites in the southeast (for purposes of decreasing the total inter-CMA distance) was not possible while also providing carrying capacity sufficient to include all GTs that are accommodated by the CMA in the southwest.

As the weight is increased to 0.1, the inter-site distances have a larger impact on the objective function. Therefore, as can be seen in Figure 7d, the model selects four clusters that are adjacent to each other. As expected, this result is similar to the one-cluster base case and identical to the meta-clustering model constraint with a short inter-cluster distance (see Figure 6d). Compared to the selection in Figure 7c, the model now selects two additional sites (12 sites in Figure 7c versus 14 sites in Figure 6d). Although this increases the total inter-site distance value (the first summation in the objective function), the higher weight used for meta-clustering counterbalances that adverse effect.

The results of models that use the two meta-clustering formulations are quite sensitive to the specification of the objective function weight σ and constraint parameter $\bar{d}$, Therefore, it would be ideal to use those methods in close collaboration with land managers.

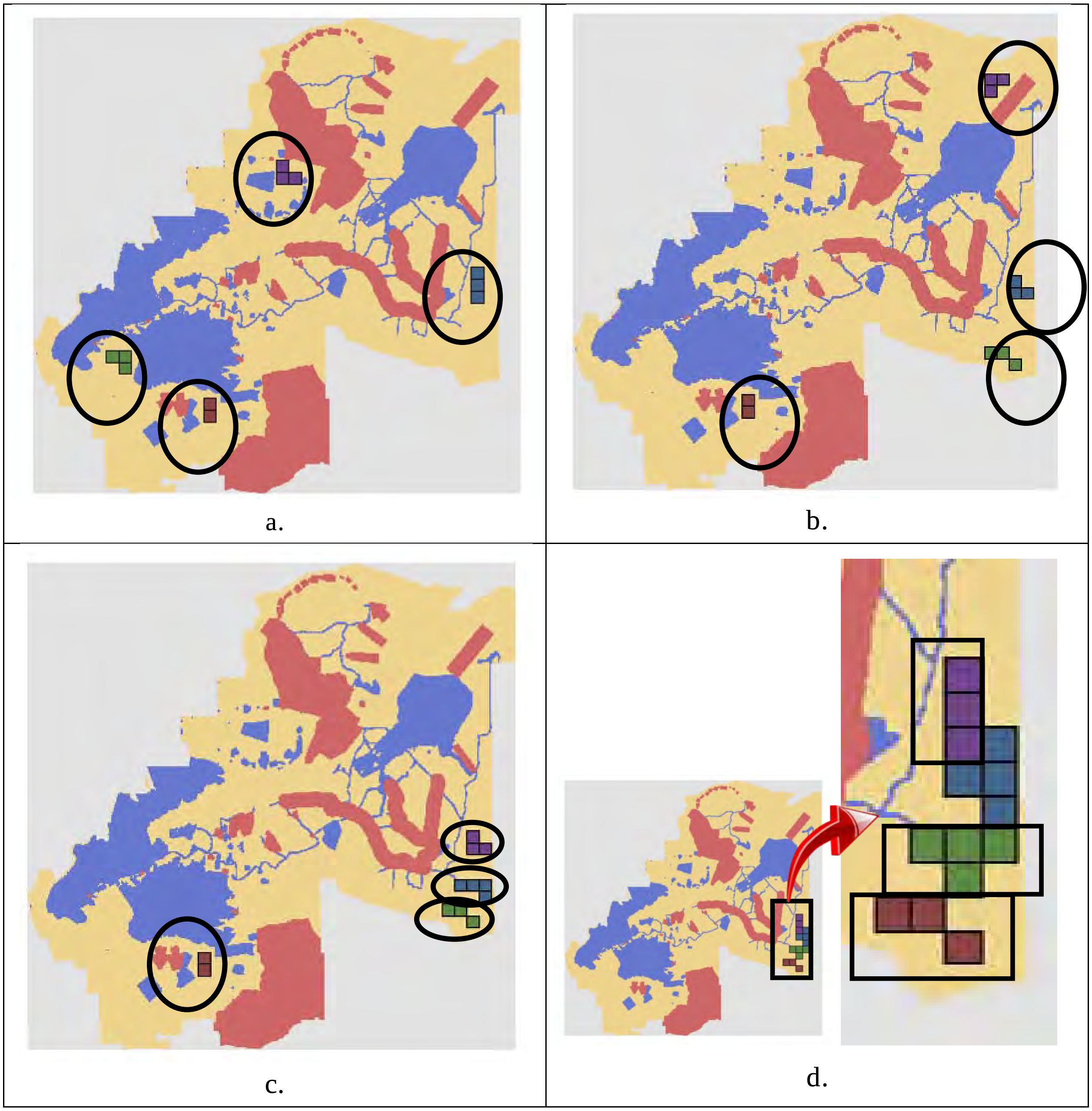

Figure 7. Meta-Clustering Model II solutions for compact CMA configurations with meta-clustering for four CMAs constraint with a meta-clustering weight of (a) 0.00; (b) 0.06; (c) 0.09; (d) 0.10. The lighter shaded areas indicate the current (blue) and proposed (red) military training areas; darker shaded areas (shown with the parcels included) indicate the conservation sites chosen by the model. Black circles identify the selected CMAs.

4 Conclusions

The linear integer programming models presented in this report were applied to a real data set derived for Fort Benning, GA, where a land-management objective is protection of at-risk Gopher Tortoise. The results of the models were consistent with technical intuition and reflected the desired outcomes for species management:

- the minimum-distance models placed the CMAs in central locations of the study areas
- the meta-clustering models select CMAs that are clustered in close proximity to each with the individual CMAs being compact.

Additionally requiring the model to minimize distances separating patch clusters can force it to select from among less-suitable parcels when the best available parcels do not meet the spatial criteria. This, in general, leads to the selection of larger CMAs with poorer compactness of some CMAs or reduced meta-clustering of multiple CMAs. Therefore, there is a tradeoff between spatial considerations and economic efficiency in optimal selection of conservation CMAs.

The grid cells that represent sites in this model are rather large, measuring 900 x 900 m. In many practical CMA design problems it may be necessary to define decision units that cover much smaller areas. Determining factors will include data accuracy, the cost of using the site for the desired purposes, and uniformity of each site in terms of habitat characteristics. The use of smaller cells (i.e., higher resolution) may considerably increase model size and computational requirements. For conservation analyses that require higher resolution, it is possible to conduct a multi-step modeling approach in which low-resolution data are used to locate the general area and then successively higher-resolution data are used for the surrounding area in successive model runs. In each successive run the model may be restricted to the area selected in the previous run, and the large grid units in that selection can be divided into sufficiently small spatial decision units to identify the specific conservation areas at desired resolution.

According to the relocation model results, it is possible to form up to four centrally placed CMAs within the new military areas that are in close proximity to the original GT habitat areas. As the allowed number of CMAs is increased, the CMAs become smaller and more compact, and they encompass higher-quality sites. However, their locations may be dispersed throughout the installation area. When a meta-clustering objective is imposed on site selection, a few more CMA locations are selected, but they are located in areas containing less-suitable habitat. These results provide general guidelines that will be useful for practical application by decision makers.

Perhaps the most important empirical finding of this study is that regardless of the spatial considerations imposed in each case, the GT habitat conservation objective can be served using a small amount of land, thus without significant sacrifice in terms of area available for training purposes.

In addition to the empirical results of this study that are of location-specific use to Fort Benning, this study has demonstrated that by successfully incorporating ecological and spatial consideration into linear site-selection models, it is possible to generate optimally designed CMA configurations using integer programming techniques. With appropriate modifications the methods introduced here are applicable to many other conservation problems involving species at risk, and they can be extended to include multiple species and multiple land uses.

References

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Appendix: GAMS Code for Mathematical Models

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```
*-----------------------------------------------------------------------
*
* GAMS Code for Ft. Benning GT Habitat Base Model
*                                  Sahan Dissanayake
*                                  sdissan2@illinois.edu
*
* This is the technical report version based on
*   "moving_tortoise_may_ver32_base_multiruns_paper_rerun_run6_calculate_numbers.gms"
*


*-----------------------------------------------------------------------
* GAMS options to limit iterations, resource use, optimality criteria
*-----------------------------------------------------------------------

OPTION   SOLPRINT = OFF;
OPTION   LIMCOL = 0;
OPTION   LIMROW = 0;
OPTION   ITERLIM=10000000;
OPTION   RESLIM=10000000;
option   optcr=0.05 ;


*-----------------------------------------------------------------------
* Declaration of Model Variables
*-----------------------------------------------------------------------

SET

         LSUPERSET all land units
                 / L1 * L1600 /
*                1600 land units arranged in a 40x40 square grid form


         COLS columns from the input data file
              / row, col, target, training, tpresent, tpossible/
*                Identifies the columns from the excel file containing the data.
*                This file is obtained from the ARCGIS file used to extract the
*                data (Section XXYY in the technical report)

```

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```


$ontext
 The land units that are intensively used by the military should not be
considered as potential GT habitat areas. Therefore considering only the
potential habitat sites  will decrease the computational requirements.
Though the data file identifies these military sites GAMS does not allow dynamic
subsets to be created. Therefore in an effort to reduce the computational
requirements we created two subsets, ML for the land units used by the military
and L for the potential GT habitat sites. In a further effort to decrease the
problem size we limited the potential GT habitat sites to sites with positive
GT carrying capacity. Since GT sites with zero carrying capacity will not be
selected for GT habitat areas these attempts to reduce the problem size will
not impact the solutions but will decrease the memory required to solve the
problem.

For the objective function meta-clustering model we further reduced the
potential cluster centers to be sites with at least a carrying capacity of
300 GT's. This was done to decrease the problem size. This should not effect
the solutions since in our trial runs all the cluster centers had a GT carrying
capacity value greater than 300.

$offtext

         ML(LSUPERSET)  new military land units - not suitable for GT habitat
         / L24,L25,L26,L62,L63,L64,L65,L66,L67,L68,L101,L102,L103,L107,L108,L141
,L142,L149,L150,L180,L181,L188,L189,L190,L198,L220,L221,L222,L223,L228,L229,L230
,L237,L238,L239,L260,L261,L262,L263,L268,L269,L270,L276,L277,L278,L279,L300,L301
,L302,L303,L304,L305,L307,L308,L309,L315,L316,L317,L318,L340,L341,L342,L343,L344
,L345,L346,L348,L349,L355,L356,L357,L381,L382,L383,L384,L385,L386,L387,L395,L396
,L421,L422,L423,L424,L425,L426,L427,L460,L461,L462,L463,L464,L465,L466,L467,L468
,L502,L503,L504,L505,L506,L507,L508,L544,L545,L546,L547,L548,L584,L585,L586,L587
,L588,L596,L623,L624,L625,L626,L627,L635,L636,L637,L663,L664,L665,L666,L676,L677
,L710,L711,L714,L715,L717,L741,L742,L743,L744,L745,L746,L750,L751,L753,L754,L755
,L781,L782,L783,L784,L785,L786,L787,L790,L791,L793,L794,L795,L817,L818,L819,L821
,L822,L823,L824,L825,L826,L827,L828,L829,L830,L831,L832,L833,L834,L856,L857,L858
,L859,L867,L868,L869,L870,L871,L872,L873,L874,L896,L897,L898,L899,L900,L901,L904
,L908,L909,L910,L911,L912,L913,L914,L935,L936,L940,L941,L948,L949,L950,L951,L952
,L953,L954,L975,L976,L989,L990,L991,L992,L993,L994,L1010,L1016,L1017,L1030,L1031
,L1032,L1033,L1034,L1085,L1086,L1097,L1137,L1138,L1180,L1181,L1182,L1183,L1184,
```

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```
L1219,L1220,L1221,L1222,L1223,L1224,L1251,L1252,L1253,L1259,L1260,L1261,L1262,
L1263,L1264,L1291,L1292,L1293,L1299,L1300,L1301,L1302,L1303,L1304,L1305,L1331,
L1332,L1333,L1340,L1341,L1342,L1343,L1344,L1345,L1380,L1381,L1382,L1383,L1384,
L1385,L1417,L1418,L1419,L1420,L1421,L1422,L1423,L1424,L1425,L1456,L1457,L1458,
L1459,L1460,L1461,L1462,L1463,L1464,L1465,L1496,L1497,L1498,L1499,L1500,L1501,
L1502,L1503,L1504,L1505,L1536,L1537,L1538,L1539,L1540,L1541,L1542,L1576,L1577,
L1578,L1579,L1580,L1581/



         L(LSUPERSET)  land area suitable for habitat clusters
/ L30, L69, L70, L71, L72, L73, L74, L104, L105, L106, L109, L110, L111, L113,
L140, L143, L144, L145, L146, L147, L151, L153, L154, L159, L160, L179, L183,
L184, L191, L194, L195, L196, L197, L199, L200, L218, L219, L231, L233, L234,
L235, L236, L240, L258, L259, L264, L265, L267, L271, L272, L273, L274, L275,
L280, L298, L299, L311, L312, L313, L314, L320, L339, L350, L351, L352, L353,
L354, L360, L377, L378, L379, L380, L390, L391, L397, L416, L418, L430, L456,
L470, L497, L501, L510, L534, L535, L536, L541, L542, L557, L574, L575, L576,
L577, L581, L582, L599, L615, L619, L621, L639, L671, L674, L698, L699, L700,
L702, L703, L704, L705, L718, L719, L737, L738, L739, L740, L752, L758, L759,
L778, L779, L789, L792, L797, L798, L799, L814, L815, L816, L820, L837, L838,
L839, L860, L861, L875, L877, L878, L902, L903, L907, L917, L918, L919, L939,
L947, L957, L958, L959, L984, L985, L986, L987, L988, L997, L998, L999, L1022,
L1023, L1024, L1025, L1026, L1027, L1028, L1037, L1038, L1039, L1059, L1061,
L1062, L1063, L1064, L1066, L1067, L1068, L1069, L1071, L1074, L1075, L1076,
L1077, L1078, L1079, L1087, L1098, L1099, L1100, L1101, L1102, L1103, L1104,
L1109, L1110, L1111, L1112, L1113, L1114, L1115, L1116, L1117, L1118, L1127,
L1128, L1139, L1140, L1141, L1142, L1143, L1144, L1150, L1151, L1152, L1153,
L1154, L1155, L1156, L1157, L1158, L1166, L1167, L1168, L1178, L1179, L1196,
L1197, L1198, L1207, L1208, L1218, L1235, L1236, L1237, L1238, L1248, L1249,
L1290, L1295, L1335, L1336, L1339, L1372, L1375, L1376, L1378, L1379, L1413,
L1414, L1415/
             ;

ALIAS (LSUPERSET, LSUPERSETP);
ALIAS (L, LP) ;
*Declares alias sets for all the sites and the potential GT sites


*------------------------------------------------------------------------
```

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```
* Import the data from the Excel file using GAMS-GDX
*-----------------------------------------------------------------------

*=== First unload to GDX file (occurs during compilation phase)
$CALL GDXXRW.EXE data/data6.xls par=Data rng=A1:G1601

*=== Now import data from GDX
Parameter Data(LSUPERSET, COLS);
$GDXIN data6.gdx
$LOAD Data
$GDXIN
*=== Fix variables to values from Excel file


*-----------------------------------------------------------------------
* Declare data parameters for the values imported from the excel file
*-----------------------------------------------------------------------

PARAMETER
         EXISTING_TORTOISE(LSUPERSET)  number of tortoise already present

         POSSIBLE_TORTOISE(LSUPERSET)  max number of tortoise possible to have

         DIST(LSUPERSET,LSUPERSETP)  distance between site L and site L

         X(LSUPERSET)     x-coordinate of parcel L
         Y(LSUPERSET)     y-coordinate of parcel L;

*-----------------------------------------------------------------------
* Assign the values of the data parameters based on the valued imorted from excel
*-----------------------------------------------------------------------

          X(LSUPERSET)  = SUM(COLS$(ORD(COLS)=1), Data(LSUPERSET,COLS));

          Y(LSUPERSET)  = SUM(COLS$(ORD(COLS)=2), Data(LSUPERSET,COLS));

          EXISTING_TORTOISE(LSUPERSET)  = SUM(COLS$(ORD(COLS)=5), Data(LSUPERSET, COLS));

          POSSIBLE_TORTOISE(LSUPERSET)  = SUM(COLS$(ORD(COLS)=6), Data(LSUPERSET, COLS));

```

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```
          DIST(LSUPERSET, LSUPERSETP)  = 900*SQRT(SQR(Y(LSUPERSET)-Y(LSUPERSETP))+SQR(X(LSUPERSET)-X(LSUPERSETP)));
*        The distance is multiplied by 900, the width of a grid cell in meters


*-----------------------------------------------------------------------
* Display the values of the data parameters
*-----------------------------------------------------------------------

         DISPLAY X;
         DISPLAY Y;
         DISPLAY EXISTING_TORTOISE, POSSIBLE_TORTOISE ;
         DISPLAY DIST;


*-----------------------------------------------------------------------
* Declare and assign values to model parameters
*-----------------------------------------------------------------------
SCALAR

         width   width of grid /40/
         min_habitat_size   minimum habitat size / 4000 /
         min_cluster_size minimum size per cluster / 750/
         num_clusters      numbers of clusters      /1/

         alpha the objective function weight on clustering /1/
         beta the objective function weight on minimizing movement distance /1/
         gamma the objective function weight on the meta-clustering component of the objective function /0.09/

         max_cluster_width the distance from the center for each parcel in the cluster / 3600/
*        To reduce the problem size the radius of each cluster is limited to max_cluster_width

         max_cluster_dist minimum distance between clusters for the meta-clustering model / 12000/

         poss_tort_mul possible tortoise multiplier / .5 /
*        This multiplier converts the possible tortoise index into the number of actual GT's

         large_num a large number /1000000/
*        a large number used in the model


```

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```
*----------------------------------------------------------------------
* Declare model variables
*----------------------------------------------------------------------

VARIABLE OBJ_FN_BASE objective function for base relocation model
         OBJ_FN_MIN_DIST objective function for minimum distance relocation model
         OBJ_FN_M_CLT_CONST objective function for constraint meta-clustering relocation model
         OBJ_FN_M_CLT_OBJFN objective function for objective function meta-clustering relocation model;

BINARY VARIABLE
         BELONG_CON1(L, LP) binary variable that is set to 1 if LP is a site assigned to L
         MOVED(L, ML) binary variable that is 1 if tortoises from site ML are moved to cluster centered at site L

*        The following variables are only used in the meta-clustering through objective function model
         BELONG_META_CENTER(L, LP) the assignment variable that is 1 is the cluster centered at LP is assigned to the
meta-cluster at site L
         IS_META_CENTER(L) binary variable that identifies the meta-cluster


*----------------------------------------------------------------------
* Declare the Model Equations
*----------------------------------------------------------------------

EQUATION OBJECTIVE_FUNCTION_BASE     objectve function for base relocation model
         OBJECTIVE_FUNCTION_MIN_DIST objective function for minimum distance relocation model
         OBJECTIVE_FUNCTION_M_CLT_CONST objective function for constraint meta clustering
         OBJECTIVE_FUNCTION_M_CLT_OBJFN objective function for objective function meta clustering



         CAN_SUPPORT_NEW(L)     to ensure that the tortoise that are only moved to available areas
         ONLY_BELONG_TO_CLUSTERS_CON1(L, LP) to ensure that parcels only belong to clusters
         ONLY_MOVE_TO_CLUSTERS    to ensure that GTs are only moved to clusters
         CLUSTERS_CON1          choose the number of clusters
         CLUSTER_MIN_SIZE_CON1(L)  choose the minimum size of a habitat cluster
         SINGLE_CONNECTION(L)  a site can only be connected to one cluster
         EVERY_MILITARY_IS_MOVED to ensure that tortoise from every military parcel are moved

         MIN_CLUSTER_DIST(L, LP) to ensure that minimum center distances are met

```

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```
         ONLY_ONE_META_CENTER to ensure only one meta center
         ONLY_BELONG_TO_META_CENTER cluster centers are assigned to the meta center (Ykl >0 implies Dk = 1
         CLUSTER_CENTERS_TO_META_CENTER ensures the every cluster center is assigned to the meta center ;


*----------------------------------------------------------------------
* Define the Model Equations
*----------------------------------------------------------------------

*        The objective functions
*----------------------------------------------------------------------

         OBJECTIVE_FUNCTION_BASE..  OBJ_FN_BASE =e=   alpha*SUM( (L, LP)$(DIST(L,LP)  < max_cluster_width),  DIST(L, LP) * B
ELONG_CON1 (L,LP))   ;
*        Objective function for the base relocation model

         OBJECTIVE_FUNCTION_MIN_DIST..  OBJ_FN_MIN_DIST =e=   alpha*SUM( (L, LP)$(DIST(L,LP)  < max_cluster_width),  DIST(
L, LP) * BELONG_CON1 (L,LP))
                                                          + beta*SUM ( (L, ML), DIST(L, ML) * MOVED(L,ML));
*        Objective function for the minimum distance relocation model

         OBJECTIVE_FUNCTION_M_CLT_CONST..  OBJ_FN_M_CLT_CONST =e=   alpha*SUM( (L, LP)$(DIST(L,LP)  < max_cluster_width),  D
IST(L, LP) * BELONG_CON1 (L,LP)) ;
*        Objective function for the meta-clustering by using constraint model

         OBJECTIVE_FUNCTION_M_CLT_OBJFN..  OBJ_FN_M_CLT_OBJFN =e=   alpha*SUM( (L, LP)$(DIST(L,LP)  < max_cluster_width),  D
IST(L, LP) * BELONG_CON1 (L,LP))
                                                    + gamma*SUM( (L, LP), DIST(L, LP) * BELONG_META_CENTER(L, LP))
                    ;

*        The constraints
*----------------------------------------------------------------------

         CAN_SUPPORT_NEW(L)..    SUM(LP$(DIST(L,LP)<max_cluster_width),  EXISTING_TORTOISE(LP)*BELONG_CON1(L,LP))  +  SUM(
ML, EXISTING_TORTOISE(ML)*MOVED(L, ML))  =l=   SUM(LP$(DIST(L,LP)<max_cluster_width),  poss_tort_mul*POSSIBLE_TORTOISE(
LP)*BELONG_CON1(L,LP))  ;
*        The number of GTs moved to the habitat cluster is within the carrying capacity of the habitat cluster

         CLUSTER_MIN_SIZE_CON1(L)..       SUM(LP$(DIST(L,LP)<max_cluster_width),  EXISTING_TORTOISE(LP)*BELONG_CON1(L,LP))
+  SUM(ML, EXISTING_TORTOISE(ML)*MOVED(L,  ML)) =g=  min_cluster_size * BELONG_CON1(L,L);
```

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```
*        for each parcel if the parcel is in a conservation area then the the new and existsing tortoise in the conservation area must added

         CLUSTERS_CON1..       SUM(L, BELONG_CON1(L,  L)) =e= num_clusters;
*        the number of clusters are specified

         SINGLE_CONNECTION(LP)..  SUM(L$(DIST(L,LP)<max_cluster_width),  BELONG_CON1(L,  LP)) =l= 1;
*        sites only belong to one cluster

         ONLY_BELONG_TO_CLUSTERS_CON1(L,  LP)$(DIST(L,LP)<max_cluster_width)..    BELONG_CON1(L,  LP)   =l= BELONG_CON1(L,L);
*        sites are only assigned to cluster centers

         ONLY_MOVE_TO_CLUSTERS(L,  ML)..           MOVED(L,  ML)  =l= BELONG_CON1(L,L);
*        GT in military areas are only moved to clusters

         EVERY_MILITARY_IS_MOVED(ML)..            SUM(L,  MOVED(L,ML))  =e= 1;
*        All the GT's in military areas are moved to a habitat cluster

         MIN_CLUSTER_DIST(L,  LP)$(ORD(L)  > ORD(LP))..          (BELONG_CON1(LP,  LP)  + BELONG_CON1(L,  L)  - 1)*DIST(L,  LP) =l= max_cluster_dist;
*        The clusters are a minimum distances away from each other. (For the constraint meta_clustering model)

         ONLY_ONE_META_CENTER..    SUM(L,  IS_META_CENTER(L))  =e= 1;
*        Only one meta center

         ONLY_BELONG_TO_META_CENTER(L)..  SUM(LP,  BELONG_META_CENTER(L,  LP))  =l= large_num* IS_META_CENTER(L);
*        Cluster centers can only be assigned to the meta center

         CLUSTER_CENTERS_TO_META_CENTER(LP)..        SUM(L,  BELONG_META_CENTER(L,  LP))  =g=  BELONG_CON1(LP,  LP);
*        Every cluster center is assigned to the meta center

*------------------------------------------------------------------------
* Model definition
*------------------------------------------------------------------------

* Base Relocation Model
MODEL    VER_TORTOISE_BASE  /OBJECTIVE_FUNCTION_BASE,  CAN_SUPPORT_NEW,  CLUSTERS_CON1
                              ,  SINGLE_CONNECTION,  CLUSTER_MIN_SIZE_CON1
                              ,  ONLY_BELONG_TO_CLUSTERS_CON1
```

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```
                              ,  ONLY_MOVE_TO_CLUSTERS
                              ,   EVERY_MILITARY_IS_MOVED /;

* Minimum Distance Relocation Model
MODEL    VER_TORTOISE_MIN_DIST  /OBJECTIVE_FUNCTION_MIN_DIST,  CAN_SUPPORT_NEW,  CLUSTERS_CON1
                              ,  SINGLE_CONNECTION,  CLUSTER_MIN_SIZE_CON1
                              ,  ONLY_BELONG_TO_CLUSTERS_CON1
                              ,  ONLY_MOVE_TO_CLUSTERS
                              ,   EVERY_MILITARY_IS_MOVED /;

* Meta-Clustering Using Constraint Relocation Model
MODEL    VER_TORTOISE_M_CLT_CONST  /OBJECTIVE_FUNCTION_M_CLT_CONST,  MIN_CLUSTER_DIST,  CAN_SUPPORT_NEW
                      ,CLUSTERS_CON1,  SINGLE_CONNECTION,  CLUSTER_MIN_SIZE_CON1
                      ,ONLY_BELONG_TO_CLUSTERS_CON1,   ONLY_MOVE_TO_CLUSTERS
                      ,  EVERY_MILITARY_IS_MOVED /;


MODEL    VER_TORT_RELOC_AND_META_CEN  /OBJECTIVE_FUNCTION_M_CLT_OBJFN,  CAN_SUPPORT_NEW,  CLUSTERS_CON1
                              ,  SINGLE_CONNECTION,  CLUSTER_MIN_SIZE_CON1
                              ,  ONLY_BELONG_TO_CLUSTERS_CON1
                              ,  ONLY_MOVE_TO_CLUSTERS,   EVERY_MILITARY_IS_MOVED
                              ,  ONLY_ONE_META_CENTER,  ONLY_BELONG_TO_META_CENTER
                              ,  CLUSTER_CENTERS_TO_META_CENTER /;


*------------------------------------------------------------------------
* Solve the model
*------------------------------------------------------------------------

SOLVE    VER_TORTOISE_BASE  MINIMISING  OBJ_FN_BASE  USING  MIP;


*------------------------------------------------------------------------
* Process Results
*------------------------------------------------------------------------

* Display cluster assignments
DISPLAY  BELONG_CON1.l;

* Open file to write results
```

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```
file results /results_01.txt/;
put results;


* Write results to file
*-------------------------------------------------------------------------

* The results will be written in one column
* '0' indicate a site not chosen
* '1' indicates a site assigned to cluster 1 and so on



                put "ft_benning_gt_habitat_base_model_ver_technical_report_1" /;

                put "min GT habitat size ", min_habitat_size/;

                put "minimum cluster size ", min_cluster_size/;
                put "numbers of clusters ", num_clusters/;

                put "width of the grid ", width/;

                put "alpha weight on cluster minimum distance ", alpha/;
                put "beta weight on minimizing the distance that tortoises are moved ", beta/;
                put "max_cluster_width the distance from the center for each parcel in the cluster ", max_cluster_width/
;
                put "possible tortoise multiplier (orig value range from 0-864) ", poss_tort_mul/;
                put "maximum distance between clusters ", max_cluster_dist/;


loop((LP),

      if
      (
         SUM (L, BELONG_CON1.l(L, LP)) = 0, put '0';

      else
         loop((L),
                 if( BELONG_CON1.l(L, LP)=1, put ORD(L); );
         );
```

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```
      );

);


putclose;

*-------------------------------------------------------------------------
* END GAMS FILE
*-------------------------------------------------------------------------
```

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14. ABSTRACT

Suitable habitat areas for many rare, threatened, or endangered species in the United States are found inside the boundaries of military installations. Because these same lands are also needed for conventional and emerging training requirements, there is growing need to manage military landscapes in a balanced way that can satisfy competing goals. This study introduces linear integer programming formulations that can be used as a decision-support tool for relocating multiple populations of a species at risk to clustered conservation areas inside a military installation.

The authors present a basic clustered relocation model and extend it to minimize the distances of relocation and to produce "meta-clustering" of separate conservation areas. Two meta-clustering methods are introduced, the first using a constraint and the second using a multi-objective function. The models are applied to a dataset related to the Gopher Tortoise (GT), a keystone species determined to be at risk at Fort Benning, GA. Analysis of the results is presented. The results illustrate that, using integer programming, it is possible to optimally design habitat areas that incorporate spatial and ecological consideration for species relocation where competing land uses must be supported.

15. SUBJECT TERMS
Gopher Tortoise (*Gopherus polyphemus*), threatened and endangered species, habitat, land-use planning, modeling, Fort Benning, Georgia, military installations

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